Technical Paper Addendum for DARPA Grand Challenge

Submission for the DARPA Grand Challenge Race

Team Name:	AVID-ET & SciAutonics
	(formerly SciAutonics II - TRUGGY)
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Vehicle Name:	Avidor-2004
	(formerly TRUGGY)

The original SciAutonics II Grand Challenge (GC) entry vehicle was based on a large, heavy and very powerful custom built "cross" between a **tru**ck and dune b**uggy** (hence its name: "**Truggy** "). While still staying in the general class of dune buggies, we now wish to replace the original Truggy with the "**Avidor-2004**", a much lighter dune buggy, better suited for the GC, which is based on the commercially available "Tomcar" (model TM27G) developed and produced by Tomcar, Ltd.

Should this Addendum be approved, we will be changing our team name from "SciAutonics II – TRUGGY" to "**AVID-ET & SciAutonics**" and the vehicle name from "TRUGGY" to "**Avidor-2004**"

1 System Description

1.A Mobility

1.A.1 Means of Ground Contact:

Ground contact is based on four standard wheels using rubber tires for surface friction, as shown in Figures 1-3 of the Appendix:

Front wheels: AT 25 x 8-12 ("Runflat" type).

Rear wheels: AT 26 x 12-12, 10 ply.

Front suspension: Double wishbone, heavy duty 13" (330mm) travel.

Rear suspension: Trailing arm, stabilizer heavy duty 13" (330mm) travel.

1.A.2 Challenge Vehicle Locomotion

Locomotion: Provided by an internal combustion 4-stroke 3 cylinders water-cooled engine driving the 2 rear wheels through a CVT and F/N/R gearbox.

Steering: Rank & pinion, 1.6 Rev. (576 deg.) lock to lock (27.9 ft or 8.5m turn radius)

Braking: Double hydraulic pump with vacuum amplifier, 4 drums.

1.A.3 Means of Actuation

Actuation is applied to the steering wheel, accelerator and brake pedal. All the actuators contain graphite brush DC motors, gears and shaft encoders, and are linked to the vehicle components via transmission belts or chains

Steering: A manual clutch disables the steering servo and enables a human driver to take over control for dual mode (manned and unmanned) operation.

Braking: The braking servo enables a human riding in the vehicle to still press the braking pedal for dual mode operation. If power is lost to the actuator, a spring activated piston installed in parallel to the servo is released and applies sufficient force to brake the vehicle.

Acceleration: The throttle servo enables a human riding in the vehicle to still press the gas pedal for dual mode operation. If power is lost to the actuator, a spring installed in parallel to the cable applies sufficient force to overcome the servo command.

1.B Power

1.B.1 Source of Power

The vehicle is powered by an internal combustion engine of 34 HP at 4200 rpm, equipped with two alternators providing together 135A at 24V (3240 W). The alternators are used to charge two 24V batteries each one of 56AH.

1.B.2 Maximum Peak Power Consumption

The maximum electrical peak power consumption is less than 3000 Watts.

1.B.3 Fuel

The vehicle uses a 115 liters (approx. 30 gallons) of regular (87 octane) unleaded gasoline. This is sufficient to achieve almost 400 miles of off-road driving.

1.C Processing

1.C.1 Computing Systems: Number, Type, and Primary Function of each Computing System

The computing system is comprised of a set of rugged computers that are communicating through wired Ethernet (connected to a 100 T-base switch). The operating systems are Windows 2000/XP and Linux. The architecture as outlined in the Appendix, Figure 4, maps modular functionality on computers. For most modules, we intend to use a ruggedized laptop computer.

Here is a list of the computers and their module assignment: **Vehicle control:** ruggedized laptop. **Obstacle and environmental sensing:** rugged PC with PCI interface card. **Road / path finding:** ruggedized laptop, PCMCIA framegrabber and firewire interface. **Path planning:** ruggedized laptop. **RASCAL Brain:** ruggedized laptop. A number of simple microcontrollers will be used to interface the computers to sensors and actuators.

1.C.2 Sensor Data Interpretation

The system for autonomous driving uses the sensors described in section 1.E. The principal components of this system and their interconnections are shown in the system diagram in the Appendix, Figure 4.

The Path Planning module (PPM) dynamically computes the path to be followed using information from the pre-processed maps (see section 1.D.1) and GPS/IMU tracking, "corrected" by the road/trail tracking module (RTTM). The suggested path forward is passed on to the RASCAL Brain module (RBM). If no obstacles are seen by the Obstacle Detection module (ODM), the path information is passed on to the Vehicle Control module (VCM). It interfaces with the low-level vehicle control systems (throttle, brake, steering, and gear) in order to guide the vehicle along the proposed path. The ODM "interrupts" the RBM upon detecting an obstacle. It provides spatial data, indicating obstacle distance and angle relative to the forward axis. The RBM, in collaboration with the PPM, then re-computes a path that is sent to the VCM to maneuver the vehicle around the obstacle encountered. In addition, the RBM controls vehicle speed based on attitude/environment sensing and the constraints imposed by Phaseline Waypoints (provided by DARPA).

The above-mentioned control by RBM will be accomplished through a strategy-based control. Strategies for vehicle behavior are devised based on information such as terrain type, current speed, obstacles (if any), and so on. A strategy context is maintained all the time to indicate the strategy that is being executed. When a context change occurs, such as a new obstacle detection in the path, an appropriate bit is set to indicate the changed context, and a new strategy is initiated by a lookup in a hash table. This allows for rapid change in vehicle behavior in dynamic response to environmental conditions.

The RTTM provides its information based on computer vision methods. The 2D tracking of the trail / road edge is interpreted into the 3D parameters vehicle yaw angle and offset relative to the borders of the trail / road.

1.D Internal Databases

1.D.1 Types of Maps

Using the DARPA supplied waypoint list distributed two hours prior to the start of the race, we will analyze the route and create a subset of map data along the route. These pre-processed maps will be produced through analyzing publicly available datasets from USGS such as Digital Elevation Models (DEM), Digital Line Graphs (DLG), and aerial photographs such as DOQQs in the context of the DARPA waypoints. The result of this analysis will contain micro-waypoints (additional waypoints between DARPA-provided waypoints) and information extracted from terrain features in the DEM model as to the type and gradient of the path between the micro-waypoints. These micro-waypoints and the pre-processed maps will then be uploaded to the vehicle just before the race.

1.E Environment Sensing

1.E.1 Sensors

The environmental sensors are divided into those used for sensing changes in the terrain, obstacles, roads, or other vehicles at relatively large distances and those useful at relatively short distances. The long-range sensors will be used to sense the region in front of the vehicle that is generally located in either the horizontal or vertical planes. At moderate or high speeds, the data from the long range sensors will be available in time to make changes in the heading and/or speed of the vehicle to either avoid the obstacle or to switch to a slow speed obstacle avoidance mode. The short-range sensors will be used to sense regions to the sides and rear of the vehicle as well as in front of it. They will provide input for obstacle avoidance-path planning as the vehicle moves at low speeds. The general characteristics of each of the sensors are summarized below.

Video camera – passive. A set of video cameras (pinhole lens, NTSC video, 30 fps) will be primarily used as a long-range sensors for detecting the edges of the road/trail and other vehicles in the forward direction. Their sensing horizon depends on the visibility and how they are aimed. A maximum sensing distance of up to 100 m will be achievable on flat straight paths.

LADAR – active. The LADAR system will be primarily used for detecting obstacles at large distances in front of the vehicle. It has the capability of detecting targets at a maximum range of 80 m with a range resolution of ~ 0.3 m. An infrared laser beam is mechanically scanned over an angular range of up to 180^o in 1^o steps. The frame update time is 13 ms. At a speed of 30 mph, the vehicle will travel ~0.17 m between updates. The latency when tracking targets in successive frames may be as much as 39 ms. This sensor will provide range and azimuth data for obstacles and other vehicles that must be avoided as the vehicle moves along the corridor between waypoints. As many as four LADAR units (SICK LMS) will be used for long-range obstacle detection. In this configuration, one of the units will be used for detecting obstacles within a 100^o

sector of the horizontal plane directly in front of the vehicle and either one or two units will be used for detecting obstacles in the horizontal plane of the left and right forward quadrants to provide obstacle detection when maneuvering to the left or right. One of the LADAR systems will be mounted so that the laser beam is directed forward and scanned in elevation. This will be used to obtain quantitative information about the contour of the path including both positive and negative obstacles.

RADAR – active. The RADAR system (from Epsilon Lambda) will be primarily used for detecting obstacles at large distances in front of the vehicle. It is capable of detecting targets at a maximum range of 110 m with a range resolution of 1 m. The microwave beam is mechanically scanned horizontally over a maximum angular range of $\pm 20^{o}$ with an azimuth angular resolution of 1.8^{o}. It will also have a capability to provide target elevation data over a range of 7.6^{o} with a resolution of 1^{o}. The RADAR will be used to supplement the obstacle detection capability of the LADAR system in situations where visibility is limited by dust, fog, or rain. It will also be relied upon when the LADAR system is “dazzled” by the sun.

Ultrasonic – active. The ultrasonic range finder will be primarily used for detecting obstacles at short distances on the sides, in front of the vehicle, and to the rear of the vehicle. It will rely on the diffuse reflection of ultrasonic waves from obstacles. Its maximum usable range is estimated to be 9-10 m. There will be several ultrasonic units located around the vehicle with a fixed pointing direction for each one. Use of these sensors will assure that the vehicle can sense nearby objects, even when bright sunlight or obscurants such as fog or dust temporarily disable or confuse the optical sensors. The update time for this sensor will be 100 ms. It will be chiefly used during relatively low speed obstacle avoidance maneuvers. At a speed of 10 mph, the vehicle will travel ~0.45 m between updates.

Photoelectric – active. The photoelectric sensors will be Rockwell Automation types commonly used in industrial automation, in close proximity to human operators. They emit low duty cycle pulsed LED light beams, expanded by a lens to about 1 cm diameter unfocused beams. The majority of the approximately 24 photoelectric sensors to be used around our vehicle will be of the diffuse reflection sensing types. In a few cases, retro-reflectors will be used to allow obstacle detection by interruption of light beams. Depending on the specific methods employed for installation of the photoelectric sensors, they will provide information about the presence, approximate range and location in combination, or only about the presence of the obstacle and a rough idea of the general location around the vehicle. Time modulation of the LED light sources will allow the sensors to operate in the presence of considerable external light. Their maximum usable range is 5-6 m.

Tactile – passive. Flexible bumper tactile sensors will be able to detect contact with objects at $\leq$ 8 inches around the vehicle. They will use a combination of electro-mechanical micro-switches, and/or interruption of self-contained low power light circuits to detect bumper motion in response to pressure contact. Their design will distinguish between motions due to vehicle vibrations and shaking and those due to object contact.

1.E.2 Locations

All sensors will be mounted on or within the roll cage protecting the interior of the vehicle. There will be no extensions from the vehicle via masts, arms, or tethers. As stated in section 1.A.1, the sensors will be located around the periphery of the vehicle so that range and image data can be obtained from an area of concern (AOC) that surrounds the vehicle. The AOC will have a generally elliptical shape that will extend more towards the forward direction than towards the sides or backward direction. The boundaries of the AOC will dynamically change as the vehicles speed changes. The sensors will operate continuously while the vehicle is moving. Range and/or image data will be supplied to the "RASCAL brain", where it will be combined with waypoint corridor information to determine if detected objects must be avoided. The sensors will be controlled from the ODM and the AES computers via analog and serial interfaces.

1.F State Sensing

1.F.1 Sensors for vehicle state

The state parameters of the vehicle that will be monitored are its global position via differential GPS, its local direction, orientation, and distance traveled, and its vertical acceleration. In addition, there will be direct sensing of the state of the vehicle's transmission (reverse, neutral, or forward), the steering angle, the throttle position, and the braking pressure.

The primary navigation will be through a Navcom Starfire SF-2050G DGPS receiver. It will be hooked up to a IMU (Rockwell Collins, GMC-10, alternatively a Systron Donner C-Migit III).

Differential odometer. The incremental distance traveled by the vehicle during a steering maneuver will be measured using a Hall effect sensor on the drive shaft that will provide 16 to 32 pulses/revolution. This will provide input for the steering of the vehicle with the assumption that there is no significant slippage of the tires. The precise distance traveled over larger distances such as between waypoints will be obtained from the GPS/IMU system.

Speed. For steering, the speed will be obtained from the Hall effect sensor. The position information from the GPS/IMU will provide the speed of the vehicle for travel over larger distances such as between waypoints.

Accelerometer. An accelerometer capable of sensing movements in the vertical direction will be used to monitor the roughness of the terrain. It will provide input for evaluating the maximum safe speed within the overall speed limit imposed by the way point/corridor rules.

Steering rate and angle. This will be measured using an angular encoder on the steering column. It will be used along with the input from the differential odometer, path planning information, and vehicle characteristics (such as maximum yaw acceleration) to provide autonomous steering.

1.F.2 Performance monitoring

Each module will provide data about its performance. If the performance is degraded, this will be considered by the RBM unit in choosing the appropriate strategy. The communication between modules is asynchronous, so that a failure of one component does not prevent the remaining system from functioning. If a module has "died", the absence of its communication is noted by the RBM module.

1.G Localization

1.G.1 Geolocation

The vehicle determines its geo-location using El-Op's GemiNav INS/DGPS system that uses the Northrop Grumman LN-200 IMU and Trimble Pathfinder DGPS unit.

1.G.2 GPS – Loss of Signal

In the absence of GPS data due to communication outages the IND/DGPS system is aided by a 3D-magnetometer and the vehicle's odometer. The Kalman filter of the Navigation system continuously blends the INS/DGPS data with the odometer and magnetic compass. As a result the compass and odometer are constantly calibrated and provide fairly accurate information. During GPS outages the INS uses only odometer and magnetic compass data to aid the inertial data.

1.G.3 Route Boundaries

The micro-waypoints will be calculated so that the route will stay within the given route boundaries. While driving, the system can verify that it remains within the route boundaries through its GPS and IMU. If the system realizes that it approaches the route boundary, it will slow down the vehicle. If it realizes that the chosen route would lead outside of the given route boundaries, the PPM will recalculate the route in order to stay within the boundaries.

1.H Communications

1.H.1 Wireless broadcast

Our vehicle will not broadcast any wireless transmission.

1.H.2 Wireless reception

Except receiving the E-Stop signal, GPS signals and the Starfire DGPS subscription signal, our vehicle will not receive any wireless signal.

1.I Autonomous Servicing

1.I.1 Refueling

The vehicle will not be autonomously refueled. Its fuel supply will last for the entire race.

1.I.2 Additional servicing activities

The vehicle will not be autonomously serviced.

1.J Non-Autonomous Control

1.J.1 Manual control

The vehicle has the capability to be safely driven by a human driver, by disengaging the autonomous control system and steering system. The vehicle will not support a remote control.

2 System Performance

2.A Previous Tests

The SciAutonics team has conducted tests of sensor in the Mojave desert. We have tested hand-held laser distance measurement units and have verified detection of hills and bushes. We have acquired a SICK LADAR sensor and have verified its detection capability up to a look-ahead distance of 80 m. We have verified the ability of optical sensors to detect objects within a short distance (up to 3 m).

During field trips to the Mojave desert, we have recorded more than 7 hours of video from a vehicle-mounted camera, recording the path ahead. We have ran part of these video sequences through our path tracking software. Screenshots depicting the results of this road tracking software are in the Appendix, Figure 5 and Figure 6.

2.B Planned Tests

Our vehicle exists as being manually driven. We are in the process of installing the actuators and sensors for automated driving. Our plan calls for the first automatic driving tests at the end of October 2003.

3 Safety and Environmental Impact

3.A Top Speed of Vehicle

The top speed of the vehicle is 40 miles per hour.

3.B Maximum Range of Vehicle

With a full tank of gasoline, the maximum range of the vehicle is some 400 miles.

3.C Safety Equipment on-board the Challenge Vehicle

3.C.1 Fuel Containment

Fuel containment will be achieved by using a specially enforced and protected, fully sealed and contained inside the chassis stainless steal gasoline tank designed to meet the most demanding racing car standards.

3.C.2 Fire Suppression

Fire suppression will be achieved by manually using two 1 kg each, halon fire extinguishers externally mounted on both sides of the vehicle

3.C.3 Audio and Visual Warning Devices

Audible alarm – An audible alarm shall be mounted on the vehicle that will meet the audible alarm specification defined by the GC rules.

Flashing Strobe – A flashing strobe shall be mounted on the vehicle that will meet the specification defined by the GC rules.

3.D E-Stops

3.D.1 Execution of Emergency Stop Commands

Software controlled stop: In this mode, a pre-determined procedure will be promptly executed by commanding the vehicle's speed control loop and the rate of turn control loop. The command to the vehicle's speed control loop ensures the fastest allowable stop. The rate of turn control loop ensures the safe halt of the vehicle without slippage, rotation or turning over. The system will remain in standby mode until allowed to resume.

Hard E-stop: The Hard E-stop cuts the engine and the main power circuits of all the onboard systems, while releasing the brake accumulator that operates the brakes system.

3.D.2 Manual E-Stop Switches

The vehicle has three large red colored manual, mushroom shaped E-Stop switches distributed at easily accessible locations on the outside of the vehicle. Pressing any of these switches will immediately start a Hard E-stop procedure, namely it will promptly disable the vehicle's engine and its entire electrical power system

3.D.3 Placing into Neutral

The transmission can be put in neutral with a movement of the automatic shift handle by pulling a pin marked "**Neutral**" (in bold letters). When in neutral, the vehicle can be towed.

3.E Radiators

3.E.1 All Devices that actively radiate EM energy

The LADAR system uses a class 1 (eye safe) laser to obtain range information. The laser operates at a wavelength of 905 nm and emits a pulse having an energy of ~300 µJ/m^2 and a mean power of 43.5 mW/m^2 with a minimum diameter of ~2 cm. This is less than the ANSI standard for a class I laser of <0.19 µJ to 1.2 mJ.

The RADAR system emits an FM-CW beam with a center frequency of 76.5 ± 0.2 GHz and a power of 1 mw over an area of ~100 cm^2. This is less than the ACGIH (American Congress of Government Industrial Hygienist's) safety Threshold Limit Value (TLV) of 10 mW/cm^2.

The ultrasonic sensor uses an electrostatic transducer from SensComp that operates at 50 kHz and emits ultrasonic energy with a transmitting sensitivity of 84 dB re 20 µPa/V at 1 m. This is less than the ACGIH safety TLV of 110 dB re 20 µPa.

The photoelectric sensors emit incoherent light in the near infrared (850-950 nm). They do not present an eye hazard at any distance or in any configuration.

3.E.2 Hazardous devices

Other than the vehicle itself and the fuel onboard, there are no hazardous devices.

3.E.3 Safety Measures

The maximum power radiated by the RADAR system is below the threshold limit value for the 15 GHz – 300 GHz frequency range. However as an additional safety measure the radiation will be automatically turned off when the vehicle is in normal E-Stop mode or is parked at the checkpoint. This means that whenever the vehicle is not operating in autonomous driving mode, the radar will be shut off and will not emit any radiation.

3.F Environmental Impact

3.F.1 Properties:

No single property of our small Challenge Vehicle can conceivably cause environmental damage, including damage to roadways and off-road surfaces.

3.F.2 Maximum physical dimensions

The maximum physical dimensions (length, width, and height) and weight of the vehicle are:

Width: 70"

Length: 111"

Height: 66" (net -- without the roof-mounted sensors)

Weight: when fully loaded, no more than 950 kg

3.F.3 Area of vehicle footprint

The area of the vehicle's footprint (contact area between the wheels and the ground surface) is not constant, since it depends on several varying parameters, like tire pressure, kind of soil/road, speed, etc. However, it is estimated to be no less than a total of 600 sq-cm. Thus the maximum ground pressure will be no more than 1.6 kg/sq-cm, or less than 24 psi.

Appendix

This appendix contains additional information that did not fit into the primary write-up of the technical proposal.

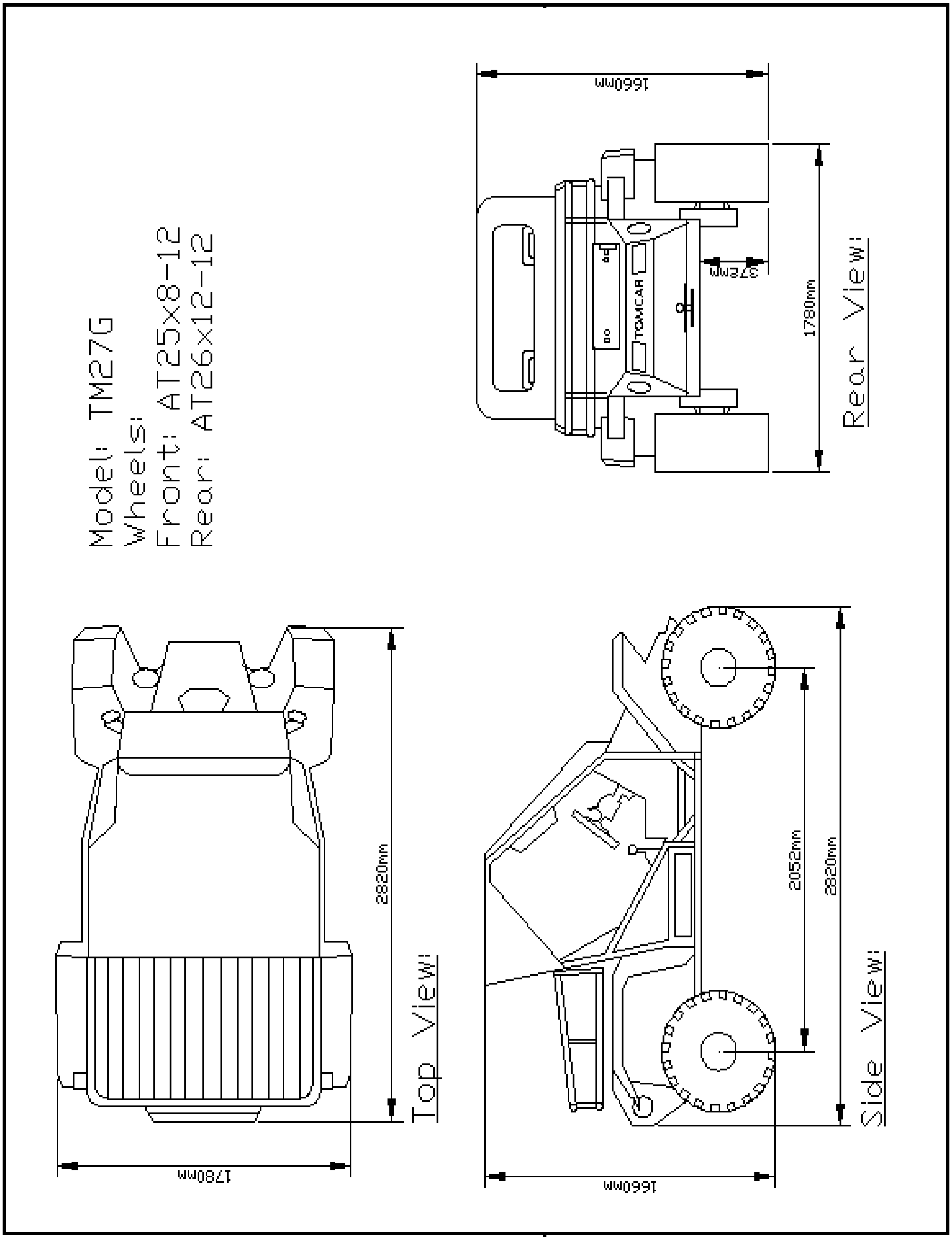

Figure 1-3. Dimensions of Avidor-2004

System Diagram

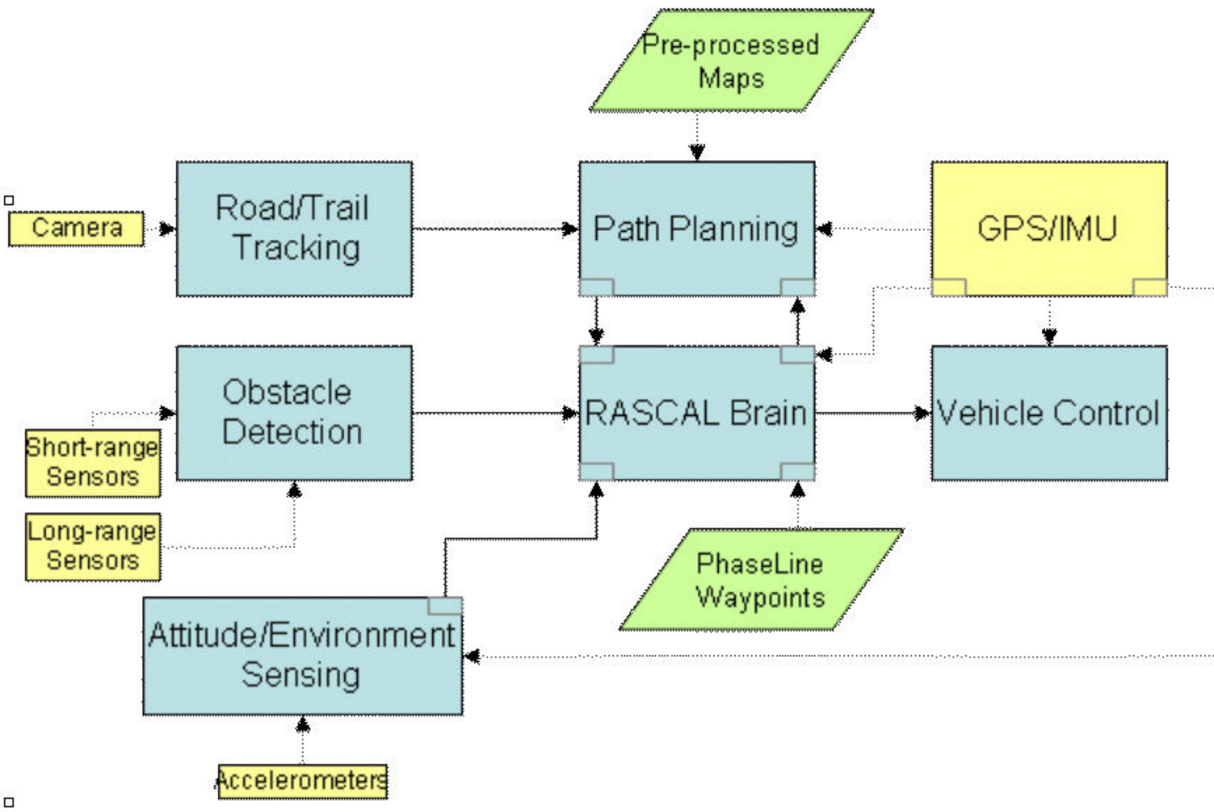

Figure 4. System diagram of the Avidor-2004 control system. This control system is identical to the RASCAL system of team SciAutonics 1. The difference between SciAutoncis 1 and SciAutonics 2 is the vehicle itself.

Results of Video Processing for Path/Route Detection

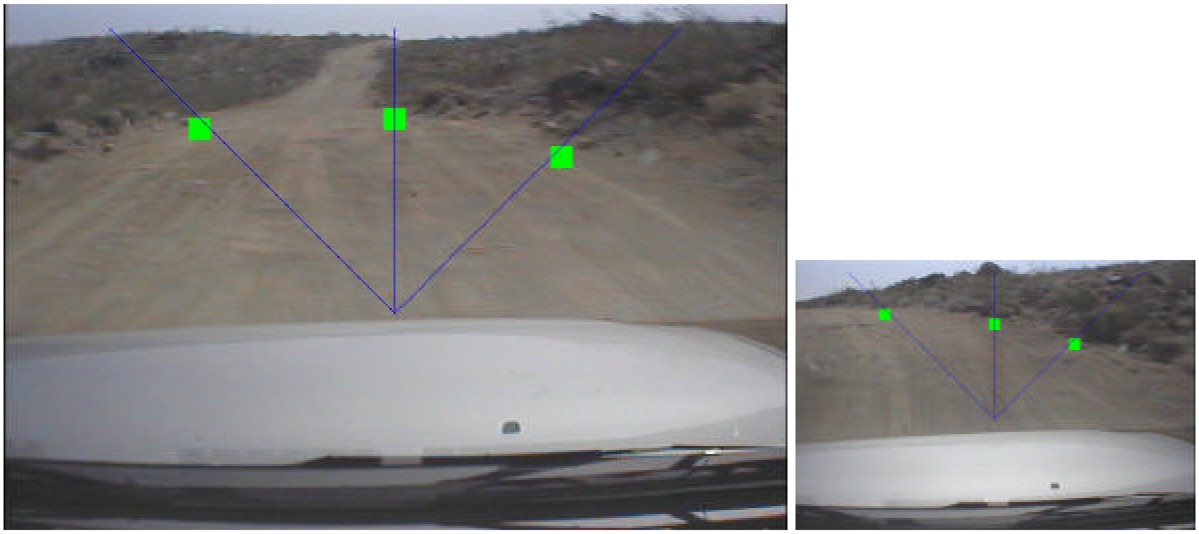

Figure 5. Screenshot of path searching. The green squares mark the detected border of the dirt road.

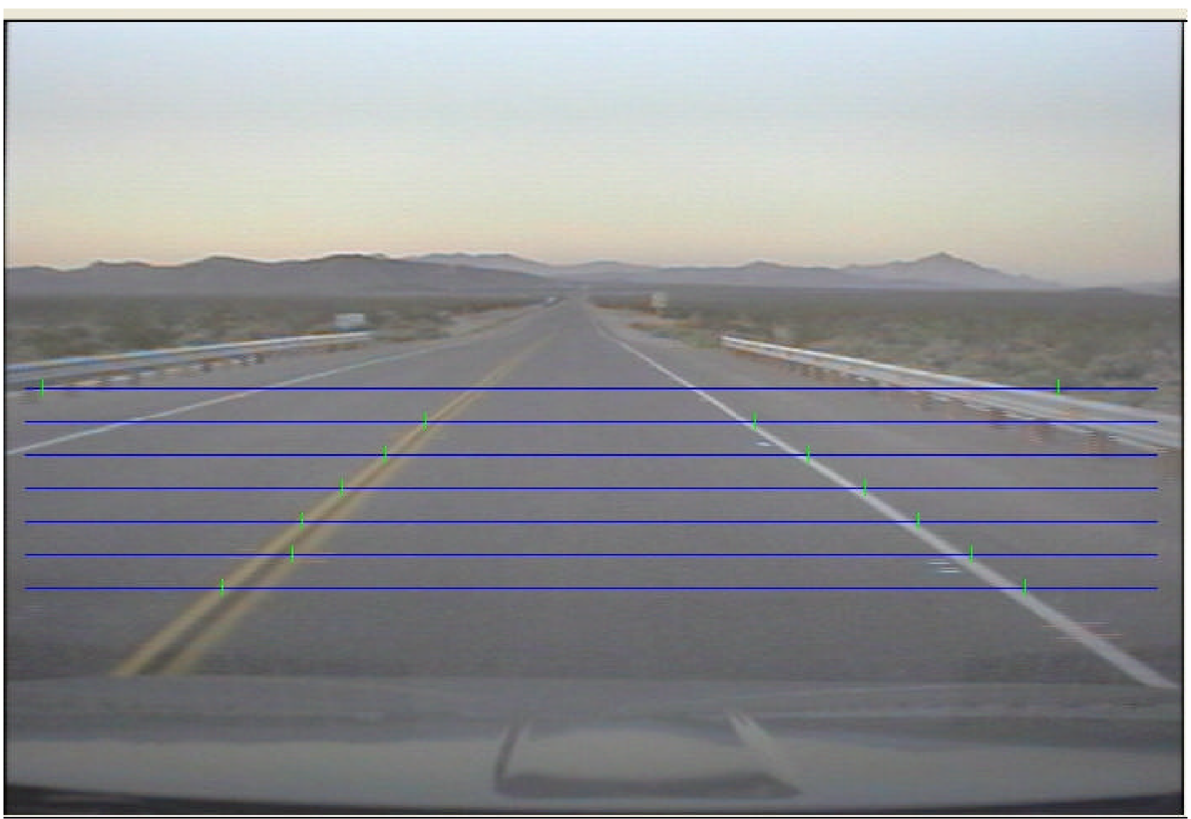

Figure 6. Screenshot of road tracking software. The detected lane markings are shown with small green vertical line segments.